DE FACTO MICROZONATION THROUGH THE USE OF SOILS FACTORS IN DESIGN TRIGGERS

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Introduction

The 1994 edition of the *National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for the Development of Seismic Regulations for New Buildings* [1] takes a step toward becoming a microzonation-based design guideline by including soils factors in its design control factors (triggers). The Provisions Update Committee of the Buidling Seismic Safety Council (which publishes the *NEHRP Recommended Provisions*) is planning to make a full conversion to this type of microzonation in the 1997 edition by including soils factors as a critical parameter in the assignation of Seismic Performance Category. This paper discusses the effect of the changes adopted in the 1994 edition of the *NEHRP Recommended Provisions*, and examines the impact of full conversion to soils-factor-based control factors.

Zonation - More Than Mere Force

Seismic zonation, as reflected in current U.S. building codes, is not merely a matter of increasing the design lateral force in parallel with increasing magnitude of expected ground acceleration. In the seismic provisions adopted in 1992 by the BOCA [2] and SBCCI [3] building codes, for example (which are based on the *1988 NEHRP Recommended Provisions*), increasingly stringent limitations on height, structural system, and permitted materials apply as expected seismic accelerations increase, along with increasingly demanding methods of analysis, levels of detailing, and quality assurance. The factor which controls most of these limitations and requirements is Seismic Performance Category (SPC). SPC is a combination of seismic acceleration (A_v or A_a) and Seismic Hazard Exposure Group (SHEG) (building occupancy or use). Items which are not controlled by SPC are directly linked to either seismic acceleration or SHEG rather than to the combination of the two factors.

The maps accompanying the *NEHRP Recommended Provisions*, which define accelerations A_v and A_a, delineate bands of seismicity that are sufficiently broad such that most local jurisdictions are encompassed by a single level of acceleration. Thus, limits on permissible building height, structural system, type of analysis, and other items are consistent throughout the jurisdiction for buildings of similar use or occupancy. For jurisdictions where the jurisdictional boundary is crossed by an acceleration contour,

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different requirements are required for similar buildings on opposite sides of the contour line. Concern is sometimes expressed that the width of the line on a code map can be several city blocks wide; where should the requirments change? Developing precise regional and city maps of anticipated seismic accelerations, which would enable microzonation to be implemented, would be an expensive effort. Another type of microzonation can be achieved without new mapping efforts, through the use of soil factors in design triggers.

Accounting for the Effects of Soil Profile - Changes in the 1994 *NEHRP Recommended Provisions*

Past earthquakes, notably the 1985 Michoacan, Mexico and 1989 Loma Prieta, California earthquakes, have vividly demonstrated that soil profile strongly affects the motions that will be experienced by a building [4,5]. In past editions of the *NEHRP Recommended Provisions*, this effect has been accounted for by increasing the design lateral force for longer-period structures (those whose design is controlled by A_v) on poor soil profiles. In the 1994 *NEHRP Recommended Provisions*, design forces are increased with poor soil profile for short period buildings (those controlled by A_a) as well.

New soil profile definitions have been adopted based on recommendations generated at a Site Response Workshop sponsored by the National Center for Earthquake Engineering Research, the Structural Engineers Association of California, and the Building Seismic Safety Council on November 18-20, 1992 [6]. Briefly, the soil definitions are:

A Hard rock with measured shear wave velocity, $v_s > 1520$ m/s
B Rock with $760 \text{ m/s} < v_s \leq 1520$ m/s
C Very dense soil and soft rock with $365 \leq v_s \leq 760$ m/s
D Stiff soil with $183 \text{ m/s} \leq v_s \leq 365$ m/s
E A soil profile with $v_s < 183$ m/s or any profile with more than 3 m of soft clay

The soil factors, F_v and F_a, associated with the new soil profile definitions vary with acceleration. Factors for use with A_v are not the same as those used with A_a, as shown in **Tables 1 and 2**. Note that for soil profile B, F_v and F_a are equal to 1.0 for all levels of acceleration. For soil profile A, the F factors are 0.8 in all instances. F_v and F_a vary with acceleration for soil profiles C, D, and E, but in all cases are greater than or equal to 1.0. In the 1991 *NEHRP Recommended Provisions*, the largest soil factor was S_4 = 2.0. The largest soil factor in the 1994 edition is 3.5. A sixth soil type, F, requires site-specific evaluation. Soil factors are not given for this soil type.

The soil factors are incorporated into design through the use of two new coefficients:

$$C_v = F_v A_v \tag{1}$$
$$C_a = F_a A_a \tag{2}$$

Shaking Intensity / Soil Profile Type	$A_a \le$ 0.1g	$A_a =$ 0.2g	$A_a =$ 0.3g	$A_a =$ 0.4g
A	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0
D	1.6	1.4	1.2	1.1
E	2.5	1.7	1.2	0.9

Table 1: Values of F_a

Shaking Intensity / Soil Profile Type	$A_v \le$ 0.1g	$A_v =$ 0.2g	$A_v =$ 0.3g	$A_v =$ 0.4g
A	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4
D	2.4	2.0	1.8	1.6
E	3.5	3.2	2.8	2.4

Table 2: Values of F_v

Soil Type	$A_a <$ 0.05	$A_a =$ 0.05	$A_a =$ 0.10	$A_a =$ 0.20	$A_a =$ 0.30	$A_a =$ 0.40
A	A_a	0.04	0.08	0.16	0.24	0.32
B	A_a	0.05	0.10	0.20	0.30	0.40
C	A_a	0.06	0.12	0.24	0.33	0.40
D	A_a	0.08	0.16	0.28	0.36	0.44
E	A_a	0.13	0.25	0.34	0.36	0.36

Table 3: Seismic Coefficient C_a

Soil Type	$A_v <$ 0.05	$A_v =$ 0.05	$A_v =$ 0.10	$A_v =$ 0.20	$A_v =$ 0.30	$A_v =$ 0.40
A	A_v	0.04	0.08	0.16	0.24	0.32
B	A_v	0.05	0.10	0.20	0.30	0.40
C	A_v	0.09	0.17	0.32	0.45	0.56
D	A_v	0.12	0.24	0.40	0.54	0.64
E	A_v	0.18	0.35	0.64	0.84	0.96

Table 4: Seismic Coefficient C_v

For ease of application, values of factors C_v and C_a are presented in tables, reproduced here as **Tables 3** and **4**.

In the *1994 NEHRP Recommended Provisions*, C_v and C_a replace the 1991 edition products A_vS and A_aS, respectively, wherever they occur. In addition, in the 1994 edition, C_a replaces A_v and A_a in some, but not all, situations. Most of the changes result in an increase in design force. For example, C_a has replaced A_v or A_a in the following:

- calculation of the design force for short period buildings
- determination of minimum design force for anchorage of concrete or masonry walls
- determination of minimum design force for diaphragms and bearing walls
- calculation of seismic effect E
- upper limit on calculated building period
- calculation of design force for architectural, mechanical, and electrical components
- calculation of design force for foundation ties

For sites with soil type B (F_v = F_a = 1.0), the changes will not have an effect on design. For soil types C, D, and E, design forces will increase for these items above the levels used in the 1991 edition. For soil type A (F_v = F_a = 0.8), design forces will decrease.

Only one significant non-force control factor has been changed in the 1994 edition. The exemptions for one- and two-family dwellings have been linked to C_a; previously they were dependent on A_v alone. The newly revised exemptions are:

1. Detached one- and two-family dwellings that are located at sites where the seismic coefficient C_a is less than 0.15 are exempt from the requirements of these provisions.

2. Detached one- and two-family wood frame dwellings with a building height of not more than 2 stories or 30 ft (9.1 m) that are located at sites where the seismic coefficient C_a is equal to or greater than 0.15 are only required to be constructed in accordance with Sec. 9.10 (Conventional Light Frame Construction).

In regions of higher seismicity, $A_v \geq 0.15$, the change has no practical effect. However, in regions of lower seismicity, where previously all one- and two-family dwellings were exempt, some dwellings will be exempt and others will not, depending on the site soil profile.

By linking exemptions for certain types of structures to soil profile, a type of microzonation is created. **Figure 1** [adapted from 7] illustrates the soil types found in the Boston, Massachusetts area. Large portions of the city are built on man-made fill.

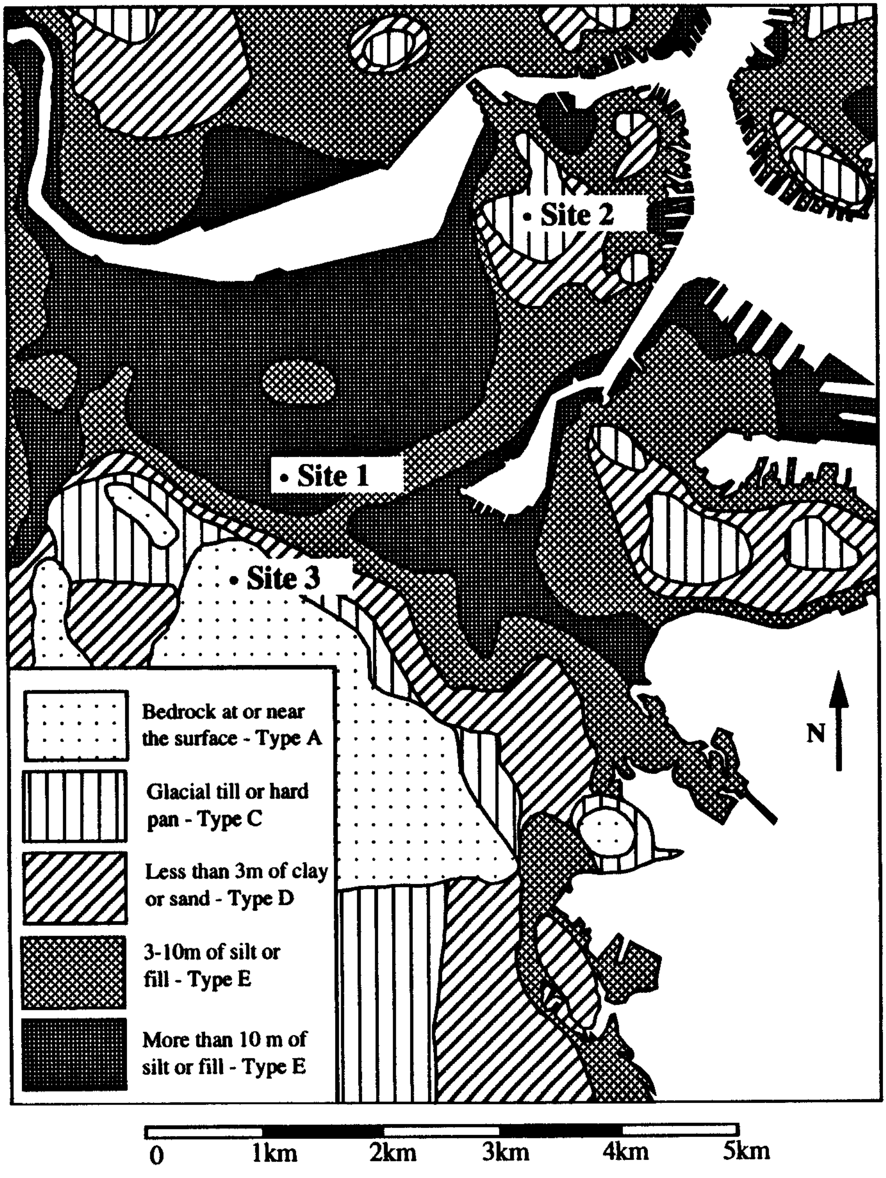

Figure 1 - adapted from Woodhouse, 1991. Map of Boston, Massachusetts and vicinity; *NEHRP Recommended Provisions* soil types assigned by authors based on physical descriptions of soil profiles provided by Woodhouse.

In other sections, the bedrock is at or close to the surface. For the purposes of illustration, probable soil profile types have been assigned by the authors based on available physical descriptions of the soil profiles.

If the changes in the 1994 *NEHRP Recommended Provisions* are incorporated into the Massachusetts building code, new houses could be built in some parts of the city without consideration of seismic effects, while in others, certain minimum seismic requirements would have to be met. Houses would be exempt only in areas where the amplifications of earthquake bedrock motions are expected to be small, whereas in the past, all houses would have been exempt. Under the new recommendations, where amplifications are expected to be large and the earthquake risk is greater, such as on the filled marshes and swamps, the houses would have to provide an appropriate level of protection against the shaking.

Where the soil profile is not known, use of soil type D is required. F_a for type D varies from 1.6 to 1.1. For areas of $0.10 \leq A_a < 0.15$, use of soil type D default values will result in houses being subjected to seismic design requirements that might have been exempted if the soil profile were known. Thus an economic issue is raised; which is less expensive, performing a geological investigation of soil profile or including seismic resistant features in residential construction? The development of publicly-available jurisdiction-wide soil profile mapping would eliminate the need for site-by-site geologic investigations for houses and other ordinary structures, but the collection of the needed information would not be inexpensive. The potential implementation difficulties and economic effects of the mandated use of soil profile type D as a default value for one- and two-family dwellings should be considered during the next *NEHRP Recommended Provisions* update cycle.

Accounting for the Effects of Soil Profile - Potential Changes to be Considered for the 1997 *NEHRP Recommended Provisions*

During the next three-year update cycle, the *NEHRP Recommended Provisions* Technical Subcommittees and Provisions Update Committee will be evaluating proposals to include soil factors in the assignment of SPC, which would result in almost every trigger in the document being linked to soil profile. This change would extend the microzonation effect beyond dwellings to all buildings.

Figure 1 can be used to illustrate the effect such a change of this type could have on the city of Boston. In a scenario where the factor C_v is substituted directly for A_v in the current definition for SPC, three different zones would be created within the city, based on the soil profile. The SPC of a building could vary from B to D. The site labeled 1 in Figure 1 is situated on over 9 m of silt or fill. An office building constructed on this site would be in SPC D. Site 2 is on very stable glacial till or hardpan; the hypothetical office building would be in SPC C. At Site 3 the bedrock is near the surface and the office building would be in SPC B. A comparison of sites 1 and 3, which are separated by a little over 1 km, illustrate the extreme differences in design and construction this microzonation would implement.

At site 1, SPC D, a concrete shear wall system, a braced frame, an ordinary steel moment frame, or a dual-system building would be limited to no more than 48.5 m in height. An ordinary moment frame of concrete would not be permitted at all on the site, nor would any building of unreinforced masonry or plain concrete. ("Special", as opposed to "ordinary", steel and concrete moment frames include details that improve the ductility of the structure.) At site 3, SPC B, there is no limit on height or structural system. At site 1, vertical or plan irregularities in the proposed structure would cause more sophisticated analysis procedures to be required. The only irregularity which must be assessed at site 3 is the existence of a weak story. At site 1, a site-specific report on potential geologic hazards is called for, and foundations must meet specific detailing requirements. At site 3, no investigation is needed and no special foundation details are required. At site 1, a quality assurance plan, including special testing and inspections, would be required. At site 3, no special consideration of quality assurance of the lateral force resisting system is necessary.

This hypothetical example illustrates one of the issues that should be considered when incorporating soil profile into assignment of SPC. Should buildings on sites with soil profile A, where $F_v = F_a = 0.8$, be allowed to be dropped into a lower SPC than had previously been required? Currently, if the *NEHRP Recommended Provisions* were used in Boston, all buildings would be SPC C or higher. In the scenario described above, SPC B would be allowed. At sites which experience has shown do not amplify earthquake shaking, is it appropriate for buildings to be designed and constructed with fewer earthquake-related limitations and requirements? In regions of low-to-moderate seismicity, should buildings on bedrock be allowed to drop to SPC A? SPC A buildings need not be analyzed for seismic forces; the only requirements are that all parts of a building be interconnected so as to be able to resist a minimal horizontal force.

Another issue that should be considered concerns the regions of lowest expected seismicity ($A_v < 0.05$). Currently, all buildings in these regions are assigned to SPC A, regardless of their use or occupancy. Should extremely poor soil conditions in these areas make seismic analysis and design mandatory? The extremely low value for acceleration in these areas is due largely to the fact that the probability of occurrence of any earthquake is remote. Given that the probability of an earthquake occurring during the lifespan of any given building in these areas is quite small, it may be inappropriate to require seismic design, even though soil conditions are poor.

Summary

By incorporating soil factors into mechanisms that control factors in seismic design procedures, buildings that are likely to suffer amplified levels of shaking will be subjected to a more rigorous seismic design procedure, while buildings on sites that are not likely to be badly shaken can be relieved of overly restrictive requirements. Some of the issues that should be addressed in calibrating a soil-based control system include:

- Should buildings on bedrock be allowed to drop into lower SPC than previously required?
- Should all buildings in areas of lowest seismicity ($A_v < 0.05$) remain in SPC A, which requires no analysis of lateral forces, or should bad soil prompt a move to SPC B or higher?
- Should any buildings in low-to-moderate seismicity areas be allowed to drop into SPC A based on good soil conditions?
- If the soil profile is not known, what default value should be used? Should the default value vary with use or occupancy? For example, should one- and two-family dwellings use the same default as other buildings?

Implementing a soil-based system of controlling design factors will create *de facto* microzonation without requiring massive mapping projects.

References

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